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Very high energy observations of the starburst galaxy NGC 253 with H.E.S.S.

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We present the result of 28 hours of observations of the nearby starburst galaxy NGC 253 with the H.E.S.S. Cherenkov telescopes in 2003. Gamma-ray emission above 400 GeV from NGC 253 was reported by the CANGAROO collaboration in 2002. We find no evidence for very high energy γ-ray emission from this object and we derive upper limits on the flux above 300 GeV of 1.9×10^{-12} photons cm^{-2} s^{-1} for a point-like source and 6.3×10^{-12} photons cm^{-2} s^{-1} for a source of size 0.5° as reported by CANGAROO, both at a confidence level of 99%. These upper limits are inconsistent with the spectrum reported by CANGAROO. The expected very high energy γ-ray emission from this object is discussed in the framework of a galactic wind propagation model.

1. Introduction

NGC 253 is the nearest spiral galaxy outside the Local Group (d = 2.5 Mpc) and is considered as a prototypical starburst galaxy. The cosmic-ray energy densities are expected to be $E_\mathrm{c} \geq 100 \times E_\mathrm{c}^\mathrm{gal}$ (where $E_\mathrm{c}^\mathrm{gal} \sim 1\,\mathrm{eV\,cm^{-3}}$ is the value in our galaxy) (Völk et al. [14]) due to the high rates of massive star formation and supernova explosions in the so called 'starburst regions', making them interesting candidates for γ-ray sources. For NGC 253 Blom et al. [2] obtained an upper limit of 3.4×10^{-8} cm^{-2} s^{-1} above 100 MeV from EGRET data.
At VHE (E>100 GeV), the CANGAROO Collaboration claimed an extended gamma-ray signal with an rms angular size estimated as 0.3-0.6° (Itoh et al. [7]), somewhat larger than the optical size of the galaxy ($28' \times 7'$). The differential energy spectrum (Itoh et al. [8]) was described by: $dF/dE = (2.85 \pm 0.71) \times 10^{-12} \times (E/1\,\mathrm{TeV})^{-3.85\pm0.46}$ cm^{-2} s^{-1} TeV^{-1}, with a corresponding flux above 400 GeV of $\approx$ 1.4×10^{-11} cm^{-2} s^{-1}, or $\approx$ 15% of the flux of the Crab Nebula above the same threshold. This detection was interpreted as inverse Compton emission, implying the existence of an extended halo of multi-TeV CR electrons around NGC 253 (Itoh et al. [9]). However, 32.5 hours of observations were also made on NGC 253 by the HEGRA Collaboration and no signal was detected. They could derive a flux upper limit of $F_\gamma(> 5.2\,\mathrm{TeV}) < 1.3 \times 10^{-13}$ photons cm^{-2} s^{-1} at 99% confidence (Götting [5]). The detection of NGC 253 by CANGAROO, along with the theoretical expectation of very high energy γ-rays from starburst galaxies, motivated the observation of this object with the High Energy Stereoscopic System (H.E.S.S.).

2. H.E.S.S. results

H.E.S.S. is an array of four 13 m diameter telescopes, each equipped with 960 pixel (5° field-of-view) cameras (Hinton [6]). Commissioning of the array in Namibia (at 1800 m above sea level) began in 2002 and the array was completed in December 2003. Observations of NGC 253 were made during the construction of the H.E.S.S. array. After run quality selection and dead time correction, 28 hours remain (24.6 hours with 2 telescopes and 3.4 hours with 3 telescopes). The mean zenith angle of observations was 14°. Only events where at least two telescopes provided shower images were used in the analysis to enable stereoscopic reconstruction.

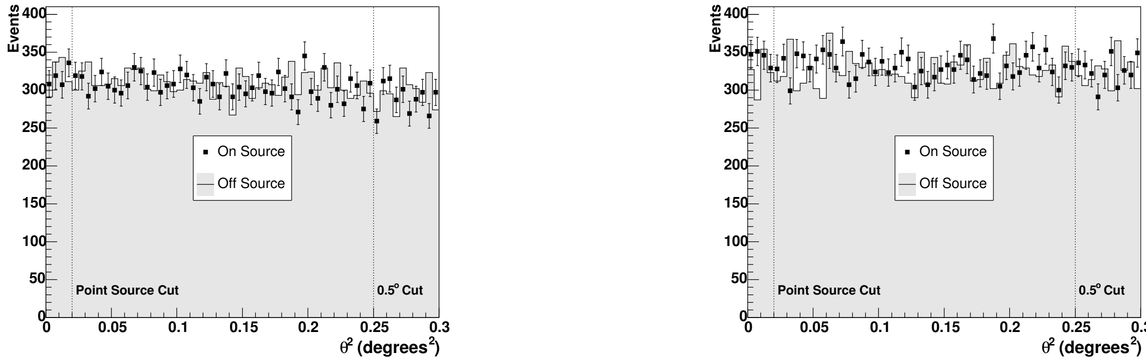

Figure 1. Left: Angular distribution of γ-like images relative to the centre of NGC 253 ("On") and relative to the background control region ("Off") for Analysis 1. Events are plotted versus the squared angular distance to give equal solid angle in each bin. Background curves (histograms) are determined relative to points 1° away from the source position. Right: as for upper figure but using Analysis 2.

Two independent methods have been applied to search for γ-ray emission in this dataset.
The first analysis (referred to as Analysis 1) is a "HEGRA"-like analysis (Aharonian et al. [1]) based on the Hillas parameters. Since the observations were taken in wobble-mode (with the target source offset by 0.5° from the tracking position of the telescopes), the events pointing to the symmetrical position with respect to the centre of the camera were used for background measurement.
The second analysis (referred to as Analysis 2) employs a different reconstruction method based on a simple 3D-modelling of an electromagnetic shower assuming rotational symmetry (Lemoine-Goumard [10]). For each event, eight parameters of the shower are reconstructed including the transverse standard deviation referred to as "3D-width". The background subtraction is then performed independently in each bin of the FOV using a maximum likelihood method based on the knowledge of the 3D-width distributions of gamma-rays and background events (Lemoine-Goumard [11]). For these two analyses, the standard calibration and image cleaning have been used.
Figure 1 shows the distribution of the squared angular distance (θ^2) of γ-ray candidates from the centre of NGC 253 for the whole data set. The distributions for the on-source and background measurements are consistent; no evidence for a γ-ray signal is seen. The vertical dashed lines in this figure indicate the positions of the standard H.E.S.S. γ-ray selection cut for point-like sources ($\theta < 0.14^\circ$) and a much wider cut (at 0.5°) at the approximate extent reported by the CANGAROO collaboration.
Figure 2 shows integral flux upper limits calculated assuming a spectrum of photon index -3.85 (as reported by CANGAROO) and following the method of Feldman & Cousins ([4]). Flux limits are shown for point-like and extended emission (0.5° radius) for Analysis 2. Also shown are CANGAROO-II integral data points derived from the differential spectrum given by Itoh et al. ([8]). Above 300 GeV we derive 99% confidence flux upper limits of 1.9×10^{-12} photons cm^{-2} s^{-1} for a point-like source and 6.3×10^{-12} photons cm^{-2} s^{-1} for a source of radius 0.5°. The upper limit curves derived from Analysis 1 are similar in shape with somewhat higher values at 300 GeV: 2.2×10^{-12} photons cm^{-2} s^{-1} (point source) and 6.9×10^{-12} photons cm^{-2} s^{-1} (0.5°).

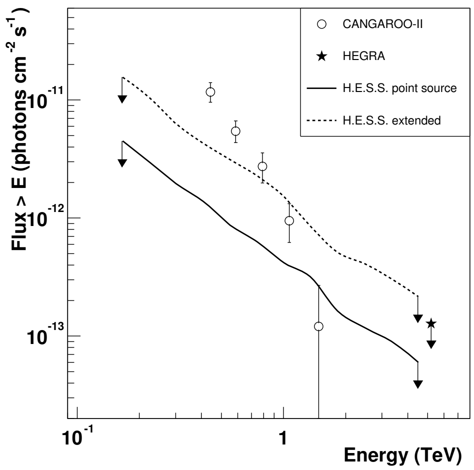

Figure 2. Upper limits from H.E.S.S. on the integral flux of γ-rays from NGC 253 (99 % confidence level) from Analysis 2. Curves for point like emission (solid lines) and for a source of 0.5° radius (dashed lines) are shown. CANGAROO integral data points (derived from the differential spectrum given by Itoh et al. ([8])) and an upper limit from HEGRA (Götting [5]) are shown for comparison.

3. Discussion

Following Weaver et al. [16] we assume the central starburst (SB) region to be a cylinder of radius $R = 150$ pc and height $H = 60$ pc in the plane of the galaxy, with an outflow that is collimated by a massive molecular torus into the vertical direction, perpendicular to the disk. The outflow velocity V_{wind} is not very well known, with "*minimum* reasonable values between 300 and 600 km s^{-1}" (Strickland et al. [13]). For the purposes of our estimates we assume here $V_{\mathrm{wind}} = 500$ km s^{-1}. The volume of the SB region is then $V_{\mathrm{SB}} \approx 4.2 \times 10^6$ pc^3. The SN rate in this small nuclear volume is estimated as $\nu_{\mathrm{SN}} = 0.03$ yr^{-1}, about as high as that of our entire Galaxy (cf. Engelbracht et al. [3]). The total mass M in the nuclear region is rather uncertain. We assume $M = 6 \times 10^7\ M_\odot$ which corresponds to the preferred value of Engelbracht et al. ([3]) and gives a density of 580 protons cm^{-3} in the nuclear region. To estimate the spatial extent and the magnitude of the gamma-ray emission as a result of the SB, we first have to consider the time scales for particle transport (t_{conv} for convection and t_{diff} for diffusion) and energy losses (t_{loss}). Assuming that the propagation properties of energetic particles in our own galaxy and its halo (Ptuskin et al. [12]) can be scaled to the SB parameters of NGC 253, one calculates $t_{conv} \approx 1.2 \times 10^5$ yr and $t_{\mathrm{diff}} \geq 1.3 \times 10^5$ yr for a 1 TeV particle. Both exceed $t_{\mathrm{loss}} = 8.6 \times 10^4$ yr. This means that CR protons with energies up to about 1 TeV behave *calorimetrically*: they lose all their energy by inelastic collisions before being able to leave the SB region. However, the increase of the diffusion coefficient with particle energy makes the particles with energies above several TeV *diffusion dominated*, which implies that they escape the SB region before interacting. The turnover point is at γ-ray energies of a few hundred GeV.

For TeV electrons the loss time is estimated as follows: the enormous far infrared (FIR) SB-luminosity $L_{\mathrm{SB}} = 1.1 \times 10^{10} L_\odot$ deduced by Engelbracht et al. ([3]) implies a radiation energy density $U_{\mathrm{rad}}^{\mathrm{SB}} \approx 500$ eV cm^{-3}. This leads to an inverse Compton (IC) loss time $t_{\mathrm{loss}}^{\mathrm{IC}} \approx 180\ (E/4\mathrm{TeV})^{-1}$ yr for the electrons of energy $E \approx 4$ TeV that produce 1 TeV γ-rays. Therefore, comparing with the proton emission, the SB region acts even more calorimetrically for the emission of TeV γ-rays via IC scattering. NGC 253 can therefore only be a TeV point source.

The hadronic γ-ray emission in this scenario simply corresponds to the total amount of CR energy created. In this picture diffusion is irrelevant below a few TeV, and the total CR energy $E_{\rm CR}$ in the SB region amounts to

$$E_{\rm CR} \approx 1.5 \times 10^{53}\ {\rm erg} \left[\frac{\nu_{\rm SN}}{0.03{\rm yr}^{-1}}\,\frac{\Theta E_{\rm SN}}{10^{50}{\rm erg}}\,\frac{t_{\rm eff}}{5\times10^4{\rm yr}}\right], \tag{1}$$

where $t_{\rm eff}^{-1} = t_{\rm loss}^{-1} + t_{\rm conv}^{-1} + t_{\rm diff}^{-1}$, and $\Theta < 1$ is the CR energy production efficiency for an average SN event with a mechanical energy release $E_{\rm SN}$. The γ-ray energy spectrum corresponds to that of the SNR sources, assumed here to be $dN_{\rm CR}/dE \propto E^{-2.1}$. Assuming the radiating TeV particles to freely penetrate the gas in and around their sources, the energy spectrum of the hadronic γ-ray flux can be calculated on the basis of eq. (13) of Völk et al. [15] by substituting our preferred values for d, M, and $E_{\rm c}$. We thus obtain $F_\gamma(>E) = 9.8\times10^{-13}\times\delta\times(E/1{\rm TeV})^{-1.1}$ photons cm^{-2} s^{-1} up to a few hundred GeV, and significantly falling off at higher γ-ray energies. The factor δ denotes the uncertainty of the assumed parameters, mainly $\nu_{\rm SN}$, M, and Θ. Assuming that $\Theta \approx 0.1$ and the average $E_{\rm SN} = 10^{51}$ erg, we obtain $0.5 < \delta < 5$. This flux, with δ=1, is similar to – in fact somewhat larger than – the H.E.S.S. upper limit for the VHE γ-ray flux, demonstrating the physical relevance of the H.E.S.S. result.

The CR electron energy produced in the SNR sources of the SB can be assumed to amount to no more than a fraction $\sim 10^{-2}$ of the energy generated in nuclear CR particles, as is the case in our galaxy.

4. Conclusion

The recently completed H.E.S.S. instrument is currently the most sensitive detector of γ-rays at VHE energies. The non-detection of NGC 253 by H.E.S.S. is surprising given the rather high flux previously claimed by Itoh et al. ([7]). From theoretical considerations of γ-ray production in starburst galaxies it appears that the H.E.S.S. limit is close to the expected flux from the NGC 253 starburst, already excluding extreme parameter values ($\delta > 1$). However, a diffusive transport away from the starburst region that is faster than assumed here cannot be excluded experimentally. The possible γ-ray flux would then be correspondingly reduced.

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